PERMANENT AUTOMATIC MONITORING OF HISTORICAL ECCLESIASTICAL ARCHITECTURE

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Abstract: At the geodetic laboratory of the Technical University of Munich the permanent automatic monitoring of historical ecclesiastical architecture has a long tradition. This paper gives an overview over the development of the various monitoring techniques from the use of invar wire methods until the application of *LEICA* robot-tachymeters. Furthermore an automatic system for permanent geodetic observations called MoSTUM (Monitoring System Technical University Munich) for the control of robot-tachymeters and additional sensors will be introduced. The experiences of the first three years of the practical use of MoSTUM in Bavarian churches are presented.

1. Introduction into the Problem

1.1. Motivation for the Installation of Permanent Monitoring Systems

Historical ecclesiastical buildings like churches are objects of great cultural value and convey a certain religious meaning. Very often historical churches show damages like tearing obviously caused by movements of the building especially subsidence, which are related to non sufficient foundation (figure 1). A renewing of the foundation is associated with immense expenses. So the goal of investigation is to check the necessity for taking action to assure the stability of the church.

First step is the investigation of the actual behaviour of moving of the church by geodetic measurements considering exterior influences on the building. This leads to the development of a static model. Under the control of further permanent precise monitoring the static model becomes verified in a second phase. During this phase of control the expert becomes enabled to define the stability of the building and the necessity of structural alterations. In the third phase the building may be controlled during the structural works.

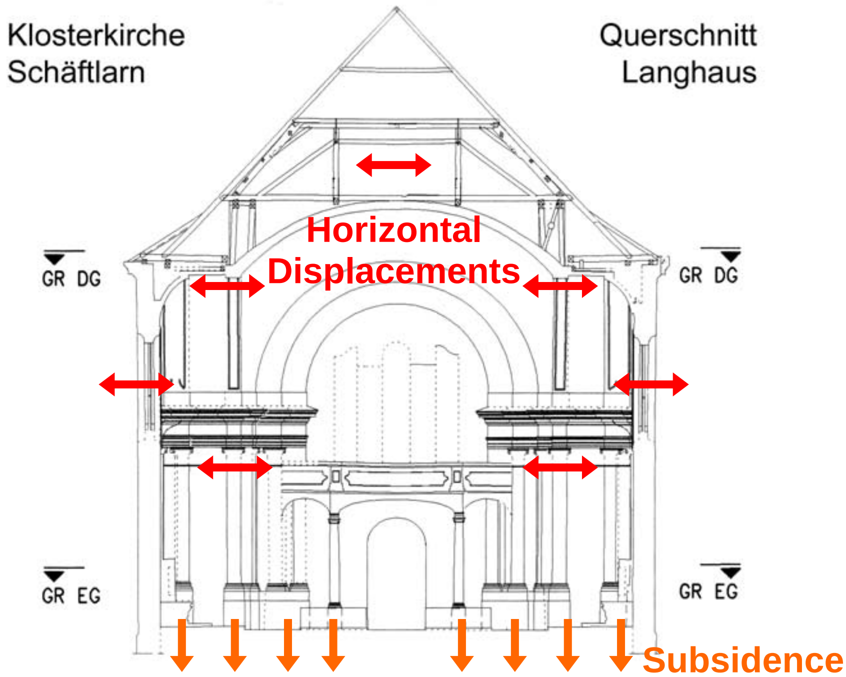

Figure 1: Unequal subsidence leads to horizontal displacements

1.2. Demands on a Permanent Monitoring System

A system for permanent monitoring of historical ecclesiastical architecture must satisfy following requirements:

- Permanent monitoring of the behaviour of the building for the detection of regular periods (Detection of daily periods, annual periods etc. ⇒ Repetitions are depending on "Nyquist Frequency")
- Permanent registration of meteorological values temperature (inside and outside the building), pressure (inside), and humidity (inside) as mean influencing values
- The concept of the system should be very flexible to allow changes in the system configuration or even the expansion of the system by additional points on demand by minimal costs.
- Sometimes it may become necessary to configure the monitoring system as an alarm system during structural works or because of too big movements of the building. This option must be considered during planning of the system.
- The required accuracies depend on the expected movements. For three dimensional observation systems in ecclesiastical buildings usually the standard deviations for each coordinate component $\sigma_x = \sigma_y = \sigma_z \leq 1\ mm$ are sufficient.
- The system must be economically convenient but also deal with the cultural meaning of the building.

2. Monitoring Methods for Permanent Observation of Ecclesiastical Architecture

At the beginning of monitoring of an ecclesiastical building, which movements are obviously caused by subsidence, it is absolutely necessary to carry out an engineering levelling of highest precision inside and outside the building. Which kind of observation system should be installed depends on the rates of expected movements, directions of expected movements, and the local conditions in the monitored building.

The most used methods for permanent monitoring of ecclesiastical architecture are:

1. Convergence measurements with invar wires
   - Analogue systems (non automatic)
   - Digital systems
2. Convergence measurements with EDM (reflectorless laser distance measurement by fix installed "Distos")
3. Inclination measurements
4. Vibration measurements
5. Application of robot-tachymeters
   - Signalisation by retro-reflectors
   - Reflectorless distance measurement

2.1. Convergence Measurements with Invar Wires

2.1.1. Analogue Convergence Measurement Systems with Invar Wires

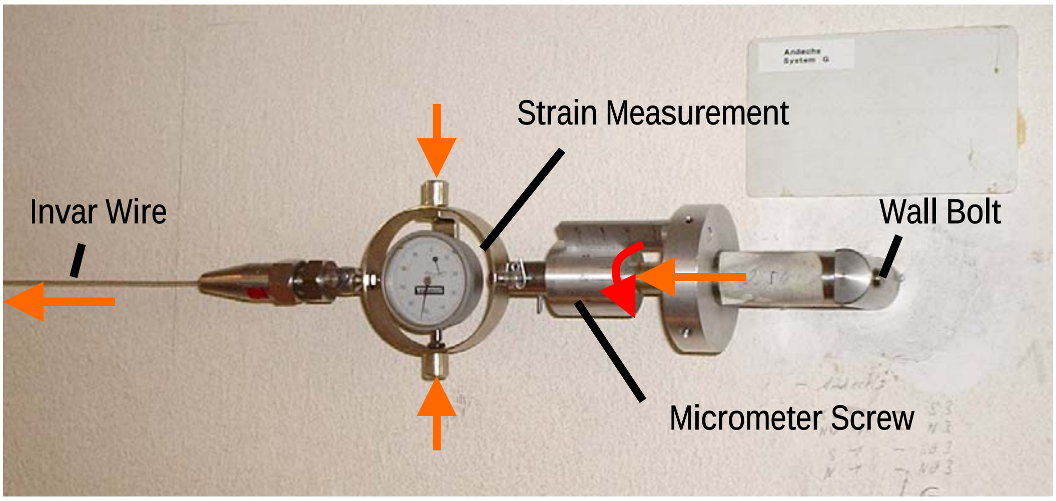

Figure 2: Analogue reading for convergence measurement with invar wire

The observation of single distances inside a church with highest accuracy ($\sigma_{\Delta s}$ < *0.1 mm)* can be realized by the use of a cross bracing wire made of invar (invar = special alloy metal with very small heat expansion). The invar wire installed between two walls by the use of massive bolts under a constant strain of *80 N* (*8 kg*). Distance variations between the bolt lead to strain variations of the wire. This strain variation changes the reading of the dial gauge in the strain ring (Resolution $1\ \mu m \Rightarrow 0.2\ N$). The original strain of *80 N* can be restored by the use of the micrometer screw. The distance variation can be read directly at the micrometer screw (Resolution *1/100 mm*, Range *5 cm*) [4].

To let non specialists do the readings, the micrometer screw is set to a fixed value at the beginning of the measurements and just the changes of the strain are read at the dial gauge. The conversion of the strain changes into distance changes is realized by the use of a calibration function determined before in the Geodetic Laboratory [4].

Usually the analogue reading of the system is realized once a day. The manual collected data is transferred to the Geodetic Laboratory by fax. The data processing is carried out monthly.

For calibration of the system it is necessary to install an identical invar wire as comparative length in the Geodetic Laboratory of the TU Munich. Once a year the invar wires of the buildings are dismounted and calibrated by static convergence measurements with the comparative length.

The advantages of this system are the high accuracy (*$\sigma_{\Delta s}$ < 0.1 mm)* and the good reliability. But this method delivers just an one-dimensional information of relative distance changes. Furthermore invar wires have to be mounted inside the building. These wires can be destroyed or are just bothering for the visitors of the historical architecture. The configuration of the monitoring system can not be changed easily. But the biggest disadvantage is the manual reading.

2.1.2. Digital Convergence Measurement Systems with Invar Wires

To debug the big disadvantage of manual reading, the dial gauge in the strain ring is replace by a displacement sensor produced by Heidenhain (Resolution $1\ \mu m \Rightarrow 0.2\ N$). The output of a *TTL*-signal allows cable length of up to *100 m*. An interface box converts the *TTL*-signal into *RS232*. The system in situ is controlled by a PC. The rate of data sampling depends on the expected movements. Beside the distance variations also the temperature inside and outside the building is measured by digital thermometers. To complete the equipment in situ the monitoring system is featured with a battery backup and surge protection for independent power supply during electrical outage. The PC sends the collected data to the Geodetic Laboratory by e-mail once a day. The data analysis is carried out in postprocessing.

There is an alarm option to send warnings when the detected movements reach critical values. The warning can be send as e-mail or given as optical or acoustical signal directly in the building. This signal could be used for example to warn construction workers during necessary renovations.

Such a monitoring system is installed in a church in the monastery of Altomünster. There are nine invar wires installed inside the church (fig. 3a & 3b)

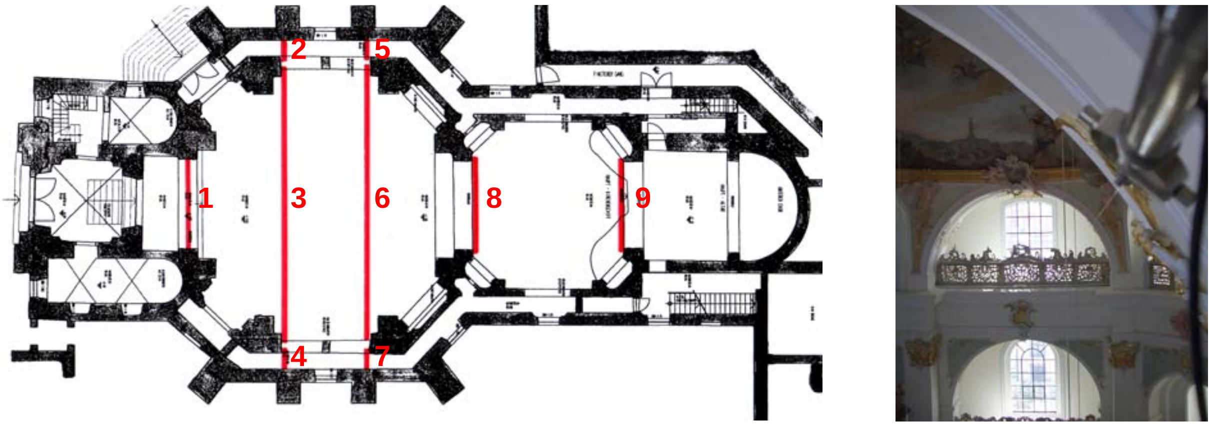

Figure 3a & 3b: Convergence measurements with invar wires in the Minster of Altomünster

The results of the digital convergence measurements with invar wires in the Minster of Altomünster are shown in Figure 4. The graphic shows the high accuracy of $\sigma_{\Delta s} << 0.1\ mm$. It also shows clearly the correlations between the temperature and the changes of single distances. But it makes clear that not all distances change by the influence of the temperature.

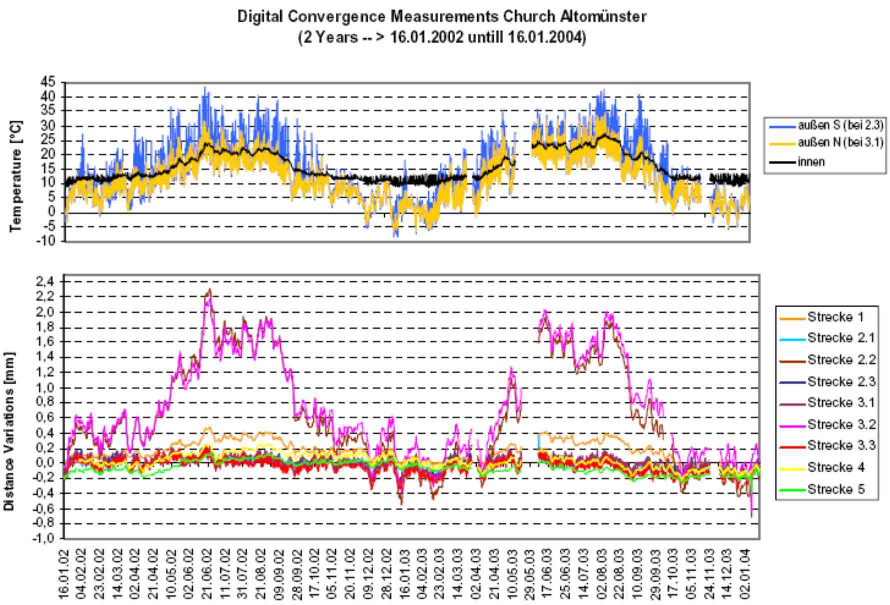

Figure 4: Results of the convergence measurements in the Minster of Altomünster

2.2. Convergence Measurements with “Distos”

Fig. 5a) *Leica* Handheld “Disto”

Fig. 5b) *Dimetix* “Disto” (heatable) for fix installation

To avoid disturbances due to installed invar wires the convergence measurements could be carried out by the use of reflectorless EDM. The handheld Laser distancemeter “Disto” produced by *Leica* (Figure 5a) could be installed permanent in a building. The guaranteed accuracy is given with $\sigma_S \leq 1.5$ *mm.* The investigations made at the Geodetic Laboratory of the TUM showed much better results of $\sigma_S << 1.0$ *mm* especially for selected instruments. For connection to a PC the “Distos” are equipped with an *RS232* port. *Dimetix* (Switzerland) offers a special version of “Distos”, which are optimized for permanent installation (Figure 5b). The “*Dimetix* Distos” possess over an integrated data bus (*RS232/RS422*) and an integrated heating. With heating the range of operation is given for temperatures from *-40°C* to *+45°C*. For data processing all rules for EDM have to be considered, especially the meteorological correction of Barrel&Sears.

Similar to the convergence measurements with invar wires the “Disto”-monitoring system in situ is controlled by a PC and equipped with modem and independent power supply. The data is also send by e-mail to the Geodetic Laboratory and an alarm option is given too (compare 2.1.2).

A monitoring system consisting out of three “Disto” lines is installed in the cupola roof of the former Benedictine monastery in Rott a. Inn. The “Distos” are mounted on special consoles with a tribrach for levelling the instrument. The data is collected in a special station with PC, modem, and independent power supply (Figure 6). The results of one year observation are shown in figure 7. A comparison of the results of the "Disto" system with the invar wire system (figure 4) shows, that the convergence system with "Distos" does not reach the excellent accuracy of the invar wire system. But in many cases the accuracy of the "Distos" is sufficient and it is to be considered that its installation and its maintenance are much more comfortable than the same works for the invar wire system.

Figure 6: Convergence measurements with "Distos" in the benedictine monastery Rott a. Inn

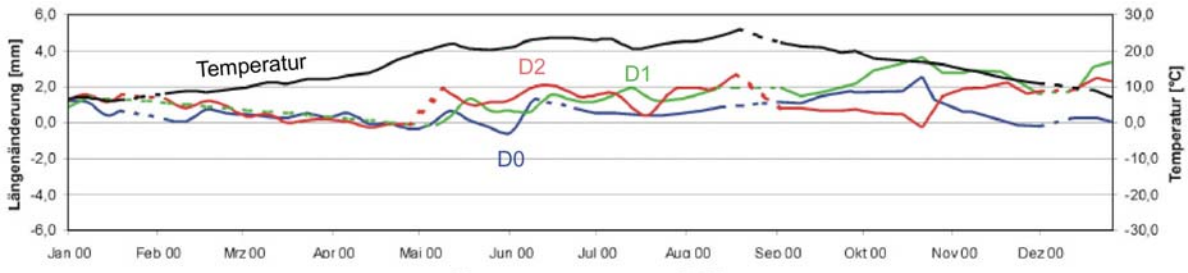

Figure 7: Result of the convergence measurements in the benedictine monastery Rott a. Inn

2.3. Inclination Measurements

Beside the horizontal displacements determined by convergence measurements there is very often the question for inclinations of exposed parts of the building like spires of churches. This question can be answered by installation of an inclination sensor. Usually a two-axis-inclination-sensor is used like *Leica Nivel20* ($\sigma_I < 0.005$ *mm/m*) (Figure 8) or even a self-calibrating two-axis-sensor like *DMT Rotlevel* ($\sigma_I < 0.0005$ *mm/m*). The sensor handling, data collection, and data transfer is integrated in the convergence system to use all features of this system (i.e. alarm option.

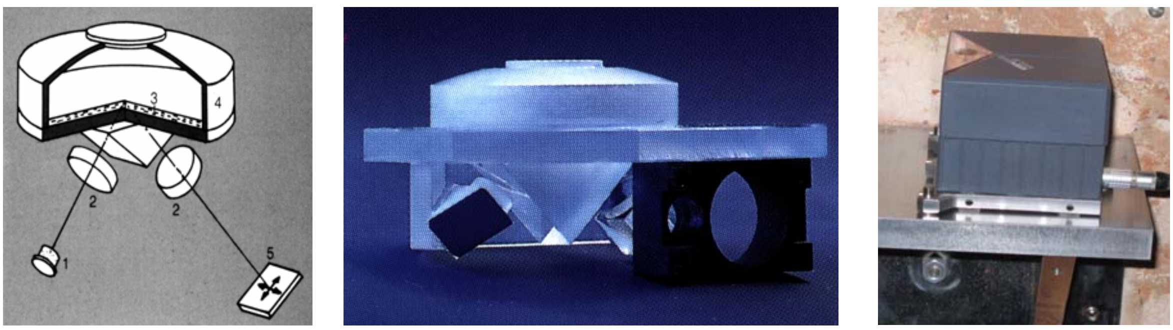

Figure 8: *Leica Nivel20* construction principle and installation in Church Spire Altomünster

Figures 8 shows an example for a *Leica Nivel20* installed in a church spire. The plot of the inclinations in x- and y-direction and also the temperature at the sensor are given in Figure 9.

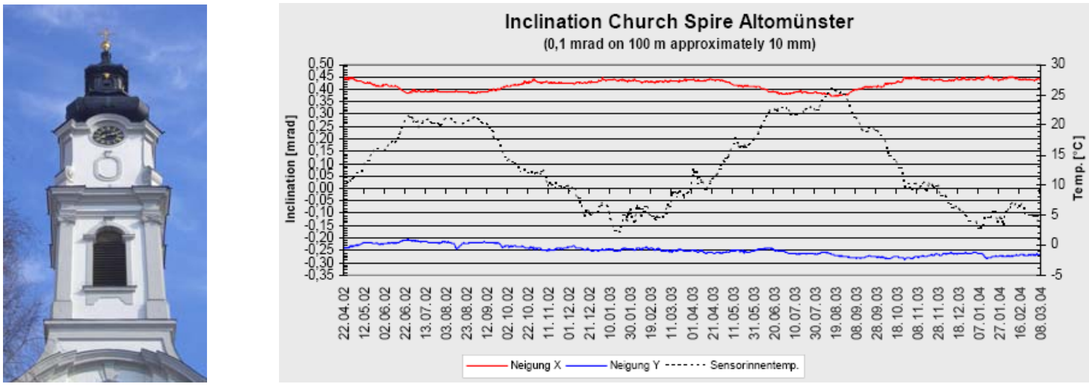

Figure 9: Results of permanent inclination measurements in Church Spire Altomünster

2.4. Vibration Measurements

In some cases the dynamic behaviour of a church under the influence of high periodic loads is to be investigated. This can be realized by the use of a laser interferometer [3]. An example is given with the investigation of the cupola of the Wieskirch. At the Wieskirch there was the suspicion that special loads on the cupola lead to critical periodic movements. The investigations with a laser interferometer HP5526A showed, that the ringing of a bell leads to periodic movements of the building in exact the frequency of the bell tone, but that the amplitude of the displacement never reached critical values (Figure 10).

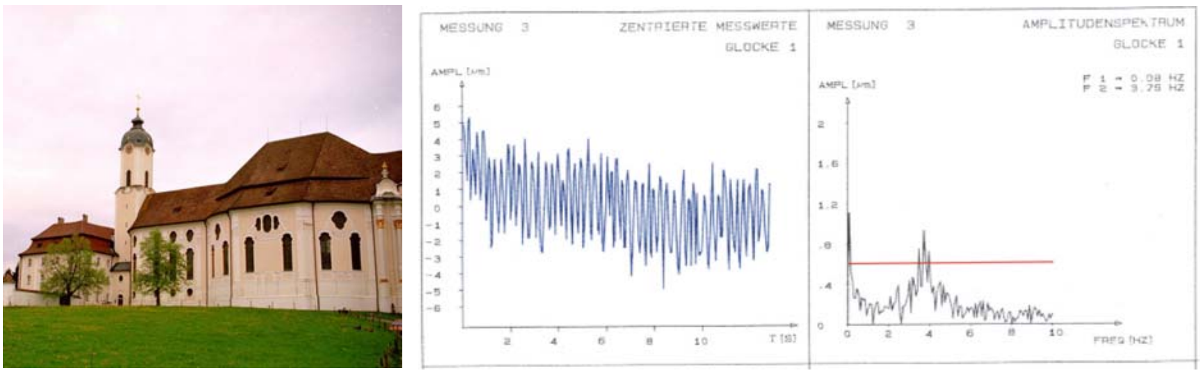

Figure 10: Results of vibration measurements with laser interferometer in Church Wieskirch

2.5. Application of Robot-Tachymeters

At the geodetic laboratory of the Technical University of Munich (TUM) an automatic system for permanent geodetic observations called MoSTUM (Monitoring System TUM) was developed. MosTUM bases on the application of *LEICA* Robot-Tachymeters with “Automatic Target Recognition” (ATR), especially the *TCA2003* ($\sigma_{Hz,V} \leq 0.15mgon$, $\sigma_s \leq 1\ mm{+}1\ ppm$). Furthermore additional sensors for detection of exterior influences like meteorological values are supported. A very often used meteorological sensor is the *Reinhardt DMT 1MV*, which is a combined sensor for temperature ($\sigma_T \leq 0.3°C$), humidity ($\sigma_H \leq 2\%$), and pressure ($\sigma_P \leq 0.8\ hPa$). Additional sensors for temperature measurement can be connected to the *DMT 1MV* because of the integrated data logger (Figure 11). So the climatic circumstances can be recorded at several points of interest in and outside the building.

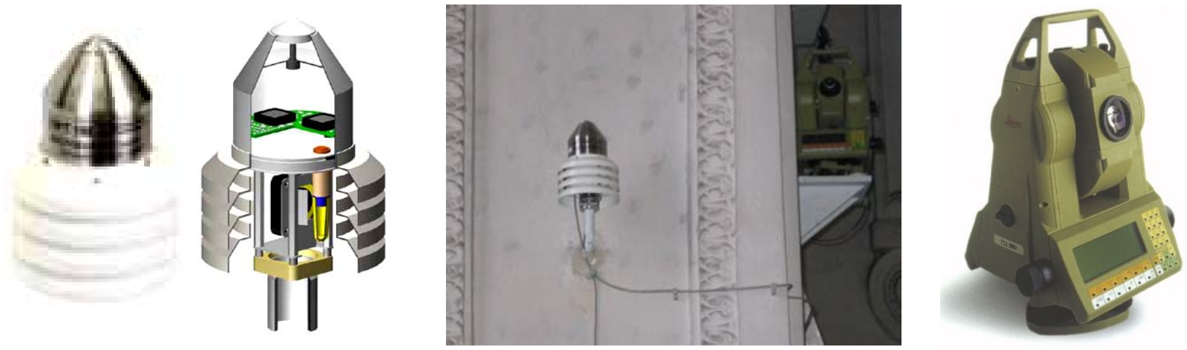

Figure 11: Sensors: *Reinhardt DMT 1MV* (left) and *Leica-TCA2003* (right)

The console for the robot-tachymeter should be installed inside the building at a possibly stable position with direct sight lines to all points of interest (object points). To avoid steel sight lines to the object points the tachymeter should be installed close to the level of the object points. The experience told us, that the most stable position is given in the back of the church at a massive wall of the tower. To assure the stability of the console, some fixed points should be installed as reference. The most fixed area in a instable church is given close to the groundlevel. The stability of the reference area is to be controlled from time to time by engineering levelling of highest precision.

All object and reference points are fitted with retro-reflector prisms. There are two sorts of prisms offered by *Leica* given with different accuracies: standard prism *GPR1 (<<1mm)* and mining prism *GPR112 (<1mm)*. In several investigations in the Geodetic Laboratory no significant difference in quality of both prisms was detected. (The mining prism is equipped with a membrane to avoid steaming up under wet conditions.) Very often the visitors view on the ecclesiastical architecture should not be disturbed by the target prisms. So the prisms have to be varnished before installation (Figure 12).

Figure 12: Leica-Prism GPR112 (<1mm) and GPR1 (<<1mm), varnished and installed

Sometimes there is no chance to find a position for the tachymeter from which there are direct sight lines to all points of interest. From economic point of view it is seldom possible to install a second tachymeter. So there was the idea to divert the sight line from tachymeter to prism by the use of a plane mirror. In the year 2003 the first investigations under practice conditions were realized with plane surface mirrors in the church of monastery Schäftlarn. Meanwhile a second system of mirrors an prisms is installed in the Jesuits Church in Landshut (Figures 13 & 14). The shifts of the indirectly observed prisms are computed by vector analysis. To detect possibly translations of the plane mirrors, there must be a directly measured prism installed in the surrounding of the mirror. An actual diploma thesis deals with the investigation of the geometry of the monitoring system under the view of the propagation of errors. The goal is to find the perfect constellation of the prisms and the mirrors, so that the observed shifts of the points are not affected by rotations of the mirrors.

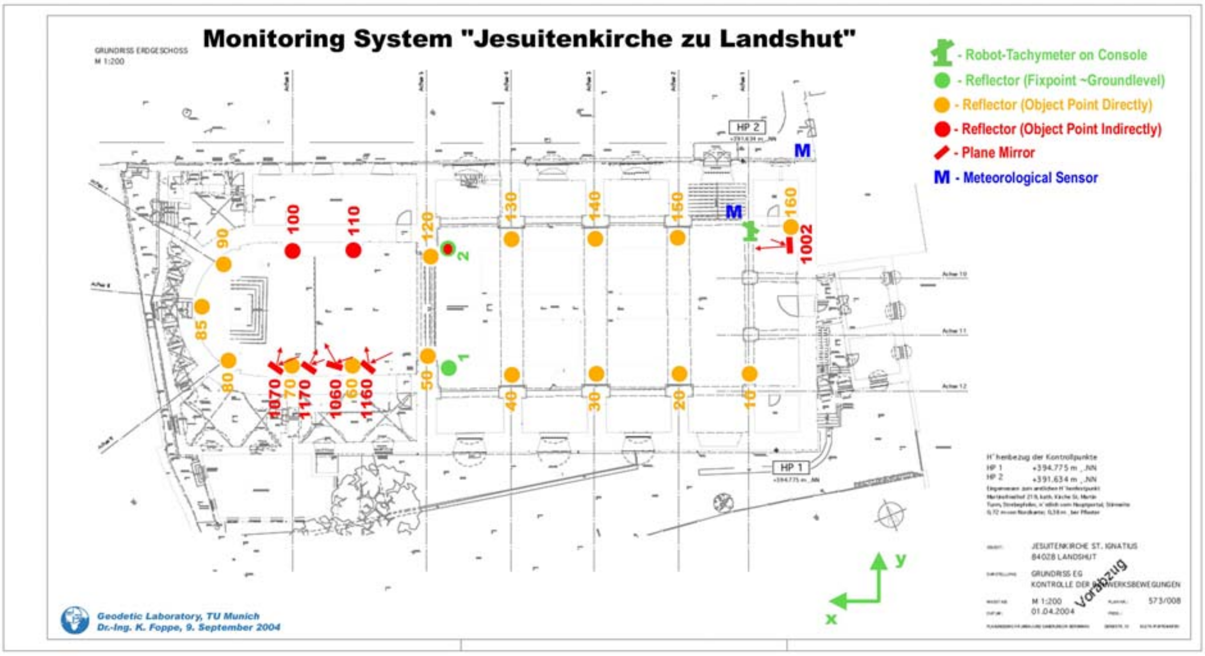

Figure 13: Constellation of the monitoring system in the Jesuit's Church in Landshut

Figure 14: View on the monitoring system in the Jesuit's Church in Landshut

The monitoring system is controlled by the MosTUM software, which was developed at the Geodetic Laboratory. Therefore a PC station with separated power supply was established in the engine room of the organ. The data transfer and the maintenance are realized via internet by a separate phone line. There is also an alarm option. By the use of GSM mobile phone modems it is possible to send short messages (SMS) about the system status directly to the responsible user of the system. In case of power blackout the full system is supported by an independent power supply for at least *2h30'*.

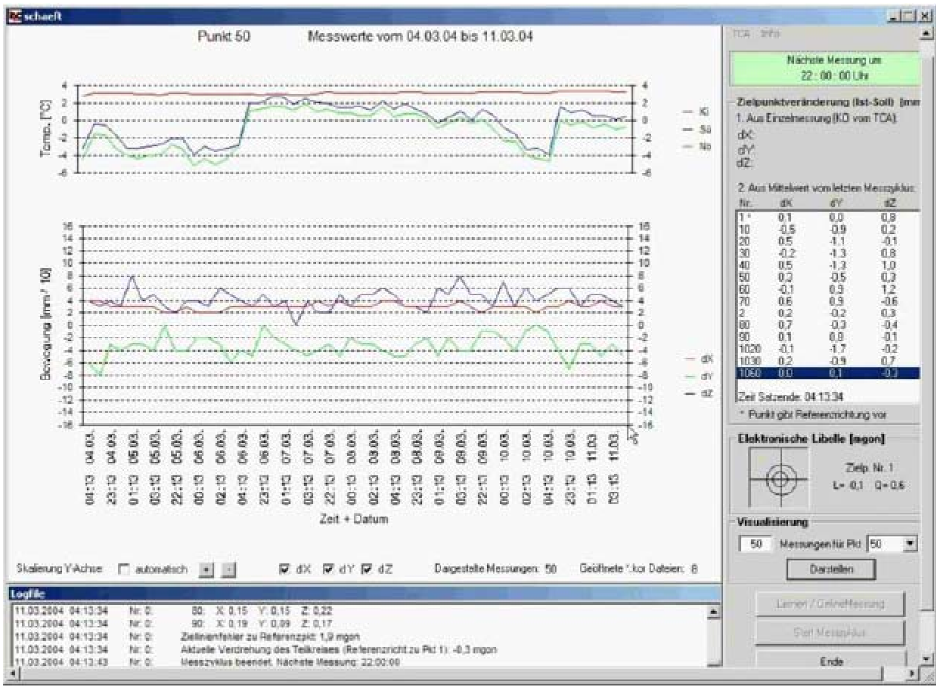

Figure 15: View on the monitoring system in the Jesuit's Church in Landshut

After the installation of the sensors and of the object points a first "zero epoch" measurement has to be measured to teach the system. This "zero epoch" is the reference for all following measurements. Figure 15 shows the view on the control panel of MosTUM.

MosTUM is an easily mutable system. There is no problem to change the configuration of the object points or to import additional points. So even in cases of changes in the behaviour of the building there is no problem to adapt MosTUM by minimal costs.

Meanwhile MosTUM is installed in three important Bavarian churches. In one case of a very big church MosTUM is running with two Leica TCA2003 simultaneously. The connection of both tachymeters is realized by an intern network. In all installation the system runs stable and reliable. The experiences of the first three years of the practical use of MoSTUM in Bavarian churches delivers accuracies for the object points of $\sigma_x = \sigma_y = \sigma_z \leq 1\ mm$.

3. References

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